COMPUTER SIMULATION AND QUALITY IMPROVEMENT

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COMPUTER SIMULATION IN THE PRODUCTION AND TREATMENT OF POLISHED GLASS

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The results of a joint project by Glaverbel Czech JSC and the Department of Machines and Robots for Glass Production at Liberec University (Czech Republic) are presented. The corrugation test is objectivized for making more accurate quality assessments of float glass directly on the production line. The processes involved in the production of large-size multilayer glass as well as the reasons for and the sources of the cracking and breakup of glass during autoclaving are analyzed. Computer simulation of the deformational characteristics of the racks in the production of large-size multilayer glass has made it possible to perform calculations to optimize and maximize the strength of the rack design.

Key words: mathematical modeling, float glass, multilayer glass, autoclaving, quality control.

The results of a joint project performed by Glaverbel Czech JSC and the Department of Machines and Robots for Glass Production at Liberec University (Czech Republic) over the period 2003 – 2007 are presented in the present article. Attention was focused first on the quality of float glass in the production line and objectivizing the corrugation test. Then the processes involved in the production of large-size multilayer glass as well as the reasons for and the sources of the cracking and breakup of glass during autoclaving were analyzed.

Objective Assessment of the Corrugation of Sheet Float Glass. The quality of the finished product during the production of float glass is monitored on-line by methods that permit determining and assessing the defects in the sheet glass, such as small inclusions (stones), striae, thickness deviations of the glass ribbon, and optical distortions (corrugation). When checking the quality of the glass these defects must be characterized according to conventional (normative) criteria and the grade of the glass must be determined.

A number of methods used to assess the quality of sheet glass are based on a subjective off-line assessment of samples. This assessment is performed periodically irrespective of the production process site and is based on comparing the glass sample being evaluated with a control sample.

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The quality monitoring and control system includes the following:

detection of defects using a laser — on-line, objectively, with resolution to 0.5 mm;

online, objective determination of ribbon characteristics (width, thickness, velocity);

determination of the corrugation of the glass using the "Zebra" method — visual monitoring directly in the glass ribbon, on-line, and objectively;

determination of striation — off-line, subjectively, i.e., a control is used to make this determination;

measurement of the optical distortions — on-line, objectively;

monitoring seeds — subjective count of defects (off-line) with subsequent objective determination of the glass grade according to the number of defects found in the sample;

monitoring the tin content on the bottom surface of the glass — subjective count of the defects (off-line) on the bottom surface of the glass followed by objective determination of the grade of the glass according to the number of defects in a sample;

examination of glass samples in reflected light using a special lamp — manually conducted off-line; this is a more sensitive method than using a laser to find defects;

off-line assessment of the corrugation of the glass; this is done subjectively using references samples;

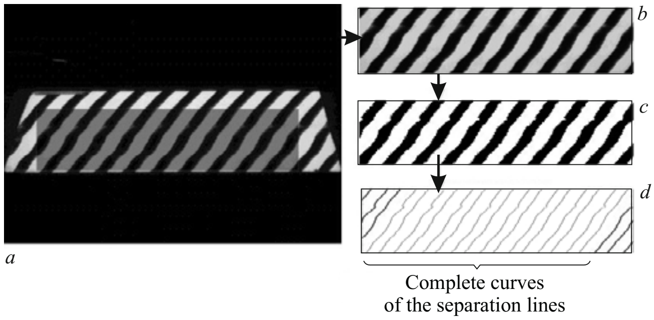

Fig. 1. Schematic order of objectivization of the corrugation test.

off-line monitoring of optical distortions along the edges of the float-glass ribbon with a subjective assessment using reference samples;

silver plating test — so-called mirror test, performed off-line; this test is a subjective assessment used to find small defects and determine the grade of the glass.

The test results are analyzed and evaluated in accordance with the operative standards. Attention is mainly focused on the defects which are monitored by an on-line method using a laser sensor in the production line; the results of the monitoring are displayed directly on the control panel of the line. Mostly, this method is used to sort glass by grade.

Objectivization of the Corrugation Test. An important quality criterion for glass is the corrugation test, which is used to assess the optical quality (corrugation of the glass across the ribbon). This test is performed subjectively (off-line) by comparing with standard samples.

The corrugation test is based on light reflection from samples located 4 m from the "Zebra" screen. The screen is a 2×1 m mat glass board with 2.5 cm wide black stripes, making an angle of 45° with the horizontal axis. The observer at the screen subjectively compares the quality of the samples against standard samples. This test is used to evaluate the total width of the glass ribbon, which is usually divided into three samples.

According to the working standards, samples with the same total width as that of the glass ribbon are assigned values that correspond to three grades of glass: 2, 2.5, and 3. The corrugation test is performed with the standard frequency of once every 2 h. Thus, this test is a subjective method of monitoring.

The aim of our investigations is to objectify this assessment.

A method was proposed and tested for making an assessment using digital frames, which were than processed with a computer program. The entire processing method can be divided into the following stages:

placing the sample to be assessed in a predetermined position;

photographing, using a digital camera, the reflection by the sample on a "Zebra" screen;

digital extraction of a selected part of the frame and conversion of this part into a black-white format;

analysis of the sample; and,

determination of the grade of the glass.

At the first stage the glass sample must be placed accurately in the require position so as to prevent distortions due to incorrect positioning of the sample from appearing in the results. It should be noted that this stage of objectivization of the assessment largely depends on the accuracy of the work performed by personnel. The next stages can be completely automated; this will make it possible to reduce the subjective assessments to a minimum.

Next, the samples are photographed with a digital camera secured in a fixed location. There are five parameters that determine the position of the camera: the position along three axes and the horizontal and vertical inclines. The camera must be secured precisely. The photographs obtained are fed into a computer, where they are processed in the TIFF standard compressed format, which prevents subsequent data loss and distortion.

Next, a frame is converted into the black-white format and a selected part which is most important for analysis is digitally segregated (Fig. 1*a*). This stage can be combined with the preceding one. For this, the camera must be adjusted so as to obtain a photograph in the black-white format with the required resolution.

A method based on generating and then interpreting the distortions of the boundary curves of the bands reflected from the "Zebra" screen (Fig. 1*b*) was developed to analyze the samples. These curves were obtained by the so-called thresholding method followed by displacement of the matrices (Fig. 1*c*). It is important to set the optimal threshold value [1 – 3] and then analyze the separated curves of the boundaries separating the black and white bands. The curves obtained can be analyzed classically using statistical methods or by means of the more modern fractal analysis [4]. Only sections with complete separation curves from the bottom face of the frame to the top face (Fig. 1*d*) were used for assessment so that no distortions would arise during data analysis.

The grade of the glass is determined on the basis of the numerical results of the analysis (one or two values) and the boundaries which have been established for different grades of glass, as determined beforehand using standard samples. The numerical values obtained can also be used as a control indicator; they make it possible to obtain a better assessment of the glass quality, and they are easier to interpret: a higher value signifies lower quality and vice versa. Two indisputable advantages of such a system are not only that the assessment results can be stored in a computer but, in addition, frames can be archived.

The complexity of the corrugation noted in [5] as the primary corrugation produced at the exit from the float bath by the lifting shafts or the less distinct secondary corrugation due to the tin flows in the bath makes it more difficult to obtain a quantitative measure of corrugation. To find a suitable

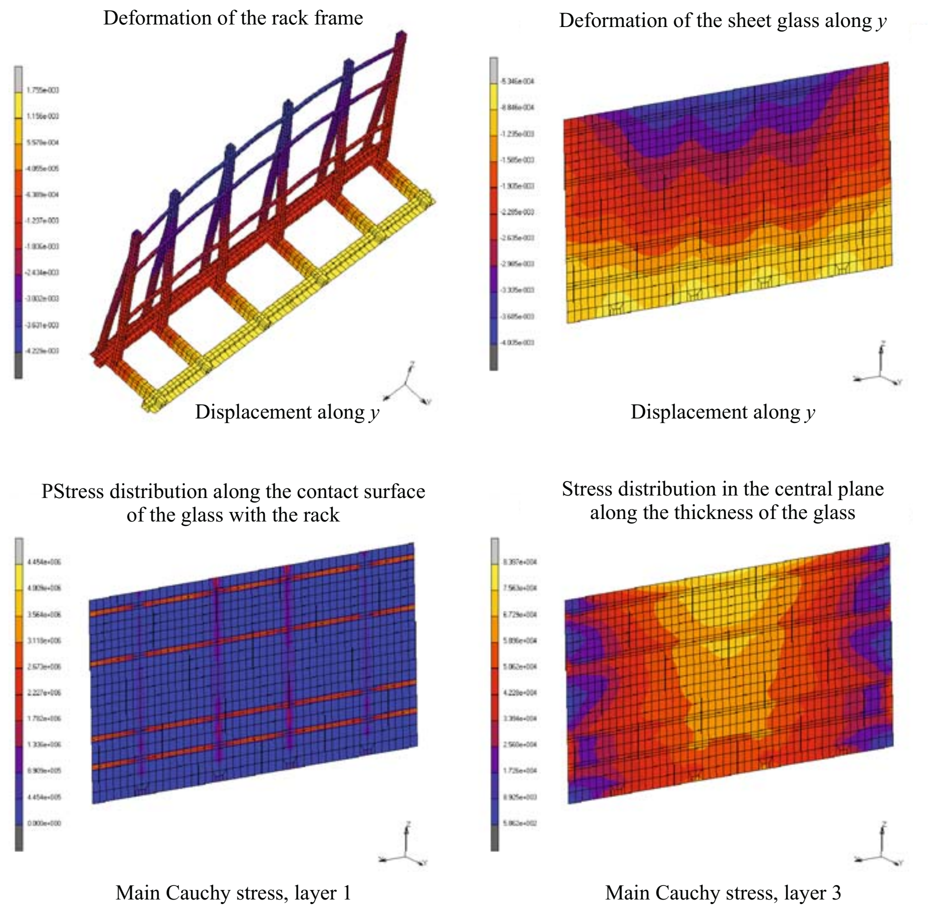

Fig. 2. Simulation results for the rack – glass sheet system.

description that takes account of the possible variants of corrugation on a standard sample the software must be adjusted to determine the weighted-mean value for a given assessment. Only after this has been accomplished is the software suitable for assessing the corrugation of glass samples and determining the glass grade.

During this work we were able to check the proposed method of objectivization of the corrugation test on extensive experimental data under laboratory and semi-production conditions. The method is now in the process of being adopted in production (based on version 4 of the applied user program). The proposed method can be widely used as a standard corporate method.

Combined Stress during the Production of Large-Size Multilayer Glass. In the production of large-size multilayer safety glass with a PVB film, mechanically and thermally induced warping of individual glass blocks can occur when they undergo treatment in an autoclave. The deformations that arise can be potential sources of cracks; this required a detailed analysis of the stresses in individual layers during the production process. Three intercoupled areas were investigated in solving this problem:

evaluation of the deformation of the racks (pyramids) under the action of the loaded glass;

analysis of the deformation and stress fields in the glass blocks during the work cycle;

analysis of the flows and temperature fields in the autoclave.

Computer Simulation of the Deformation of Racks Under the Action of Loaded Glass. A potential source of cracking of the glass is its contact interaction with the frame of the rack, which as temperature increases (approximately by 150°C) deforms under the load due to the glass mass and as a result of the different CLTEs of the glass and frame. The distribution and magnitude of the deformation fields of the racks depend on the total mass of the glass being processed (the maximum weight of the load glass is 27.5 tons), the temperature and pressure in the autoclave, the quality of the surface (levelness) of the floor, and the stiffness of the rack structure.

In this project, the possibilities of using mathematical modeling with application of the finite-element method to optimize the frame structures were checked. In our case, when we talk about analysis of the interaction of sheets of glass with rack frames, we encounter the difficulty of solving problems with deformation-type contact and the compound (mechanical – temperature) character of the load. Digital simulation in solving problems of this type encounters a number of computational instabilities, which are due to the possibility of determining the contact mathematically, setting up optimum computational steps and types of finite-elements used, the character of the boundary and initial conditions, and the material properties of the contact bodies [6]. Considerable efforts have been made to determine the configuration parameters of the computational model and to ensure that the results can be adequately reproduced [2, 7].

The simulation determined the finite-element deformation grid of the rack – sheet glass system for prescribed loading and packing conditions. Several types of loads were considered; they consisted of the most frequently encountered variants of contact between the floor of the autoclave and the rack. Numerical simulation makes it possible to observe the development of the deformation and stress fields, which make it possible to determine the main strength characteristics of the frame being analyzed and, most importantly, the stressed sheet (block) of glass. A number of problem variants, including the boundary conditions, were proposed and

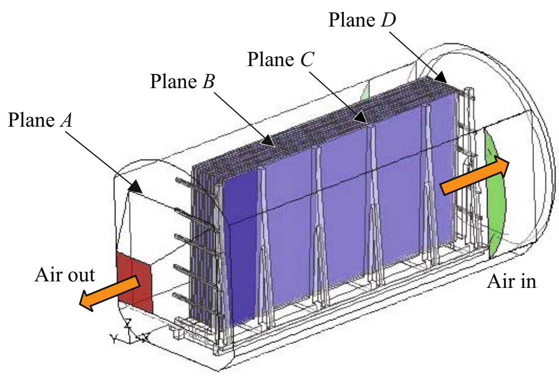

Fig. 3. Geometric model of an autoclave with a glass load.

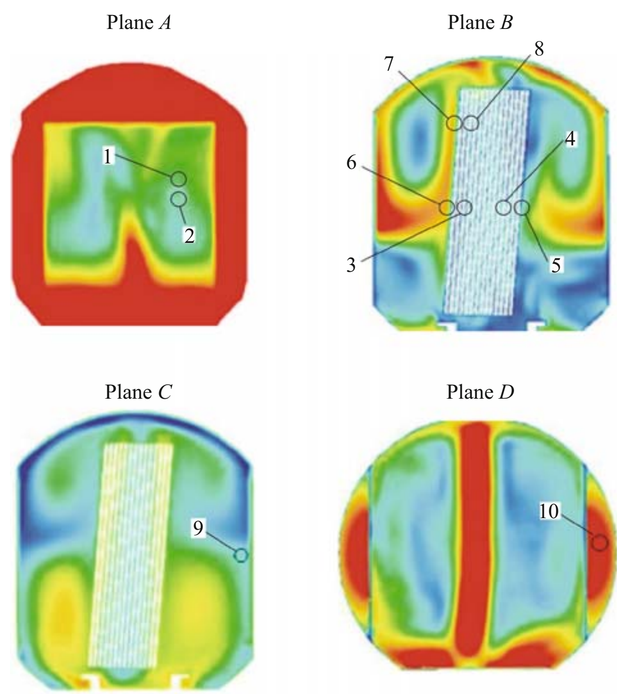

Fig. 4. Locations of the anemometers (1 – 10) in the autoclave and the distribution of the velocity fields (transverse sections of the autoclave, Fig. 3).

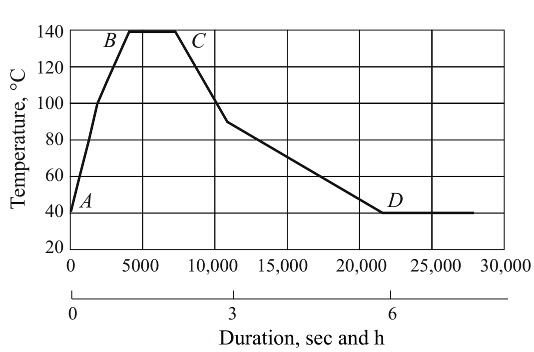

Fig. 5. Variation of the temperature during the process cycle of an autoclave.

TABLE 1.

Measurement location (in accordance with Fig. 3)	Velocity, m · sec^{-1}	
	production measurement	computer simulation
1	2.9	2.9
2	2.7	2.1
3	1.6	1.8
4	1.7	1.7
5	1.9	1.5
6	3.3	3.2
7	3.2	3.5
8	2.0	1.5
9	8.2	9.3
10	3.1	3.2

calculations were performed for them. For example, Fig. 2 displays for an ideal contact with the floor the deformation characteristics of the rack and the deformation and stress field in the loaded glass.

The calculations showed that the rack frame it is not strong enough even though it is quite massive. A glass sheet in a block placed in the rack shows the same deformation as the frame; this is a source of elastic deformations of the glass. Figure 2 shows that the tops of the middle ribs of the frame (at maximum temperature 140°C) move by approximately 3.5 mm. The calculations performed have shown that the rack structure can be optimized so as to maximize its strength. A redesign of the rack decreased the deformation by 30 – 35% of the initial value.

Computer Simulation of the Fluxes in the Autoclave During the Entire Process Cycle. The possibilities of using a CFD program to analyze the flows in the working zone of the autoclave were checked at the initial stage of the project [7]. Considering the complexity of the problem to be solved and the character of the computational model used (simplified model, which was constructed using an automatic grid generator to construct the computational grid with tetrahedral elements), it was impossible to trace systematically the character of the flows in the zone of the large-size glass loads. The results obtained gave primary information about the general character of the flows (velocity fields) in the working zone of the autoclave and simultaneously made it possible to determine the main flow directions as well as to identify the critical region.

A new computational model which includes a description of the boundary conditions was developed at the second stage [2]. Hexahedral elements were used in the glass loading zone. The geometric model developed is shown in Fig. 3. This model made it possible to construct an effective complex numerical model, i.e., to investigate the velocity profile in the gaps between the individual glass blocks.

The results of the simulation were checked under factory conditions with the fan power used in the isothermal ventila-

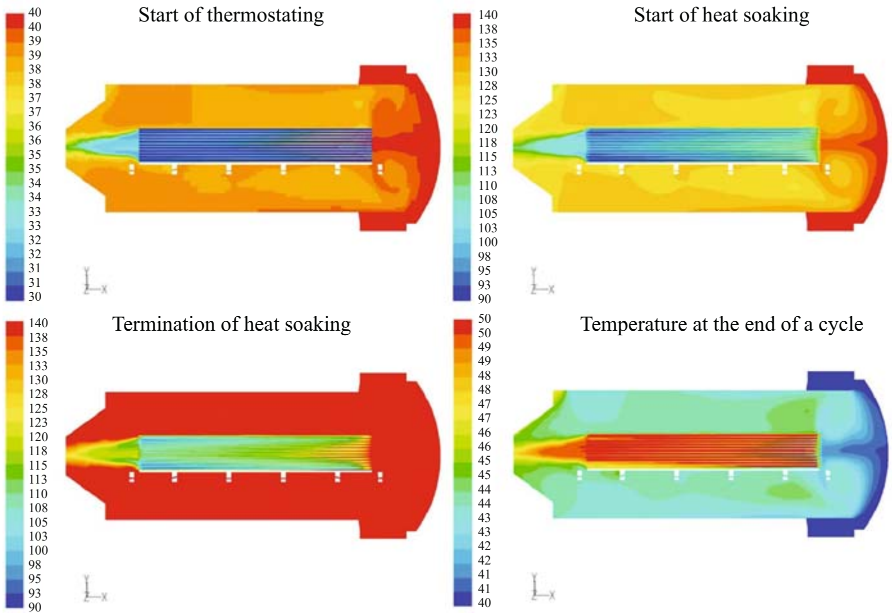

Fig. 6. Temperature field (°C) of the autoclave during the process cycle.

tion regime. Control measurements confirmed our assumption: increasing the pressure to the working level clearly has no effect on the velocity conditions in the autoclave. The measurements were performed at only ten locations in four planes (see Fig. 3) using two types of anemometers. The SCHILKNECHT MiniAir6 propeller anemometers were used to measure the velocity of the working-carrier flow in the free space of the autoclave; DANTEC 55A81 probes with DANTEC 56C17 hot-wire anemometers were used to evaluate the characteristics of the circulating air in the rack space. The arrangement of the individual probes is shown in Fig. 4. It was determined that the measured velocities satisfactorily agree with the results obtained in the simulation (see Table 1).

The flows between the glasses were evaluated only at the back end of the load near the fan (at the exit). The air flow velocity does not exceed 9 $m \cdot sec^{-1}$ at the exit from the feed channel, 3.5 $m \cdot sec^{-1}$ on the exterior surfaces of the load, and 2 $m \cdot sec^{-1}$ between individual glass packets.

The process of pressing large-size glass in an autoclave was analyzed in detail, taking account of all real conditions, at the third stage [3]. The variation of the temperature and temperature fields during the process cycle are presented in Figs. 5 and 6.

The results presented above show that the development of the temperature fields between the center and both edges of the load (inner, outer) is strongly nonuniform; but, the temperature difference remains within the limits 20 – 30°C. A temperature difference is observed in individual blocks (in the longitudinal direction) inside the load during the entire cycle, and in this case the temperature range does not exceed 20°C. The modeling performed in this work has shown that the thickness of the liners affects the course of the temperature cycle in individual blocks of glass; this thickness can be optimized effectively by the method indicated. The individual stages of the simulation can be used effectively under production conditions. However, a single computational process requires a great deal of time.

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